VOLUME 2

APPLIED PHYSICS

Optics and Wave Phenomena

Reflection and Refraction • Total Internal Reflection

Interference • Thin Films

Diffraction • Single and Double Slits

Polarization of Light

Dr. Irfan Toqeer

PhD Physics, MSc Computer Science

First Edition • 2025

APPLIED PHYSICS

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Applied Physics - Volume 2: Optics and Wave Phenomena

First Edition, 2025

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Dedicated to

My Beloved Wife Fariha

whose unwavering support and quiet strength
have illuminated my academic journey with purpose and peace

and to

The Great Physicists

Newton, Huygens, Young, Fresnel, and Maxwell
whose insights revealed the nature of light

Preface

Light has fascinated humanity since the dawn of civilization. From ancient philosophers wondering about the nature of vision to modern scientists developing laser technologies and fiber-optic communications, the study of light—optics—has been central to both our understanding of nature and our technological progress.

This textbook, *Applied Physics - Volume 2: Optics and Wave Phenomena*, continues the journey begun in Volume 1, now focusing on the wave nature of light and its remarkable behaviors. Designed specifically for undergraduate students at Riphah International University, Faisalabad, and similar institutions, this volume provides a comprehensive introduction to geometrical and physical optics.

The Journey from Volume 1 to Volume 2

In Volume 1, we explored electricity and magnetism, culminating in Maxwell's equations—the mathematical framework that unified these phenomena and predicted electromagnetic waves. Now, in Volume 2, we study light as an electromagnetic wave, examining how it reflects, refracts, interferes, diffracts, and polarizes.

This volume represents not just a continuation, but an application of electromagnetic theory to one of its most beautiful manifestations: light. The concepts you learned about waves, fields, and electromagnetic radiation now come alive in observable phenomena—rainbow colors in soap bubbles, the bending of light through lenses, the resolution limits of microscopes, and the polarization of scattered sunlight.

Philosophy and Approach

This volume maintains the pedagogical philosophy established in Volume 1:

1. Physical Intuition First: Each phenomenon is first explained qualitatively, building your intuitive understanding before mathematical analysis.

2. Complete Mathematical Development: Derivations are presented step-by-step with no gaps. Every equation is explained, and every assumption is stated clearly.

3. Connection to Reality: From camera lenses to CD players, from anti-reflection coatings to 3D movies, the applications of optics surround us. This book connects theory to the technology you use daily.

4. Visual Learning: Optics is inherently visual. This book contains extensive diagrams, ray tracings, and graphical representations to help you visualize abstract concepts.

Organization of Volume 2

The book is structured to build knowledge progressively:

- **Chapter 1** begins with reflection and refraction, the foundation of geometrical optics, including the fascinating phenomenon of total internal reflection.
- **Chapter 2** explores interference, starting with two-source interference and Young's historic double-slit experiment, then extending to thin film interference with practical applications.
- **Chapter 3** covers diffraction, showing how wave nature becomes evident when light encounters obstacles comparable to its wavelength.
- **Chapter 4** examines polarization, a uniquely wave-like property that has applications from sunglasses to stress analysis.

Each chapter builds on previous material while remaining accessible to students who have completed an introductory course in electricity and magnetism.

For Students: How to Master Optics

1. Visualize: Always draw diagrams. Optics is visual—ray diagrams, wave patterns, and geometric constructions are essential tools.

2. Work Through Derivations: Don't just read the mathematics—reproduce it yourself. Understanding how equations arise builds deep comprehension.

3. Do the Problems: Optics requires practice. Work all the examples, then try the practice problems. Solutions develop problem-solving skills.

4. Connect to Experience: Look for optics in daily life—reflections in windows, rainbows, the blue sky, polarized sunglasses. These phenomena illustrate the principles you're learning.

5. Use Multiple Resources: While this book is comprehensive, consult other texts, online resources, and experimental demonstrations to see concepts from different perspectives.

6. Study Actively: Form study groups, explain concepts to classmates, and teach what you've learned. Teaching is one of the best ways to deepen understanding.

For Instructors: Using This Text

This book is designed for flexibility:

- **Full Semester Course:** All chapters can be covered in a 14-16 week semester with 3-4 hours per week.
- **Abbreviated Course:** Sections marked with asterisks (*) can be omitted without loss of continuity for shorter courses.
- **Laboratory Complement:** Suggested experiments accompany each chapter for courses with laboratory components.

- **Problem Sets:** End-of-chapter problems are ranked by difficulty (1-3 stars) to facilitate assignment planning.

- **Assessment Tools:** Sample quiz and exam questions are available to adopting instructors.

The book supports various teaching styles—from traditional lecture to flipped classroom to hybrid online-offline approaches.

What Makes Optics Special

Optics occupies a unique place in physics. It's both practical and profound, both ancient and cutting-edge. The same principles that explained rainbows to medieval scholars now guide the design of:

- Optical instruments (telescopes, microscopes, cameras)

- Telecommunications infrastructure (fiber optics)

- Medical devices (endoscopes, laser surgery)

- Consumer electronics (CD/DVD players, barcode scanners)

- Scientific instruments (spectrometers, interferometers)

- Modern displays (LCD, LED, holographic)

Moreover, optics played a crucial role in the development of quantum mechanics. The phenomena you'll study—interference and diffraction—led to wave-particle duality and the quantum revolution. While this book focuses on classical optics, you're learning concepts that bridge to the quantum realm.

Acknowledgments

This volume benefited from numerous contributions:

- **Students** at Riphah International University whose questions and confusion revealed where clearer explanation was needed.

- **Colleagues** in the Department of Physics who reviewed chapters and suggested improvements.

- **My Family** for patience during the countless hours devoted to writing and revision.

Special thanks to the students who class-tested draft chapters and provided candid feedback that significantly improved the final product.

A Note on Conventions

Throughout this book:

- SI units are used exclusively
- Vectors are shown in bold ($\mathbf{E}$) or with arrows ($\vec{E}$)
- Light speed in vacuum: $c = 3.00 \times 10^8$ m/s
- Wavelengths are typically given in nanometers (nm) for visible light
- Angles are measured in degrees or radians as appropriate (clearly indicated)
- Sign conventions for lenses and mirrors follow standard physics conventions

Continuing Feedback

This book is a work in progress. Despite careful editing, errors may remain, and explanations can always be improved. I welcome feedback from all readers:

- Error reports (with page numbers)
- Suggestions for clearer explanations
- Ideas for additional examples or problems
- Reports of what worked well in your learning or teaching

Please send feedback to the Department of Physics, Riphah International University, Faisalabad. Your input will improve future editions.

The Beauty of Light

As you work through this book, I hope you'll develop not just competence in solving optics problems, but genuine appreciation for the elegance of wave phenomena. The interference patterns that emerge when coherent light passes through two narrow slits. The complete reflection of light at a critical angle. The polarization that reveals stress in transparent materials. These aren't just physics problems—they're windows into the deep mathematical harmony underlying physical reality.

Isaac Newton devoted much of his later career to optics, including his famous prism experiments decomposing white light into colors. Thomas Young's double-slit experiment helped establish the wave theory of light. James Clerk Maxwell's equations unified optics with electromagnetism. Albert Einstein's explanation of the photoelectric effect launched quantum mechanics. The study of light has repeatedly transformed our understanding of nature.

You're joining a tradition of inquiry stretching back centuries and reaching forward to technologies we can barely imagine. Whether your future involves research, engineering, teaching, medicine, or any field touched by optics (which is nearly all of them), the knowledge in this book will serve you well.

Final Encouragement

Optics can be challenging. Some concepts—like the phase changes in thin film interference or the intensity distribution in diffraction patterns—require careful thought. Don't be discouraged if understanding doesn't come immediately. Physics is learned by doing, by struggling with problems, by making mistakes and correcting them, by discussing with peers, and by persistence.

Remember: every expert physicist once sat where you sit now, puzzled by Snell's law or confused about path differences. What distinguishes those who master physics is not innate ability but sustained effort and genuine curiosity.

Work through the examples. Attempt the problems. Draw the diagrams. Ask the questions. Seek help when needed. Your effort will be rewarded with understanding—and understanding of how light works opens countless doors in science, technology, and pure intellectual satisfaction.

Welcome to the fascinating world of optics and wave phenomena. May your journey be illuminating in every sense of the word.

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Chapter 1

Reflection and Refraction of Light Waves

1.1 Introduction to Light as a Wave

Light exhibits both particle and wave characteristics. In this chapter, we focus on the wave nature of light, which explains phenomena such as reflection, refraction, interference, and diffraction.

Light waves are **electromagnetic waves** consisting of oscillating electric and magnetic fields perpendicular to each other and to the direction of propagation. In vacuum, all electromagnetic waves travel at the speed of light:

$$c = 3.00 \times 10^8 \text{ m/s} \tag{1.1}$$

The relationship between wavelength λ, frequency f, and speed v is:

$$v = f\lambda \tag{1.2}$$

1.2 The Nature of Light Propagation

Light propagates as a transverse wave, where the oscillations are perpendicular to the direction of travel. The wave can be described mathematically as:

$$E = E_0 \sin(kx - \omega t) \tag{1.3}$$

where:

- E = electric field amplitude
- E_0 = maximum amplitude
- $k = 2\pi/\lambda$ = wave number
- $\omega = 2\pi f$ = angular frequency
- x = position
- t = time

1.3 Law of Reflection

When a light wave encounters a boundary between two media, part of the wave is reflected back into the first medium.

Law 1.3.1 (Law of Reflection)**.** *The angle of incidence equals the angle of reflection:*

$$\theta_i = \theta_r \tag{1.4}$$

The incident ray, reflected ray, and normal to the surface all lie in the same plane.

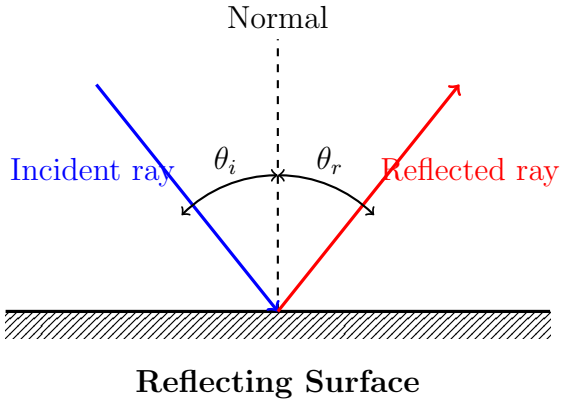


Figure 1.1: Law of reflection: $\theta_i = \theta_r$

1.3.1 Types of Reflection

1. Specular Reflection: Occurs on smooth surfaces (mirrors). Light reflects at definite angles according to the law of reflection.

2. Diffuse Reflection: Occurs on rough surfaces. Light reflects in many directions, though each ray still follows the law of reflection locally.

1.4 Index of Refraction

When light travels through a medium, it interacts with the atoms of that medium, causing it to slow down.

Important Equation

The index of refraction n of a medium is defined as:

$$n = \frac{c}{v} \tag{1.5}$$

where c is the speed of light in vacuum and v is the speed of light in the medium.

Since $v < c$ in any material medium, we always have $n > 1$.

Key Point

Common indices of refraction (at $\lambda = 589$ nm):

- Vacuum: $n = 1.0000$ (exactly)
- Air: $n \approx 1.0003 \approx 1$
- Water: $n = 1.33$
- Glass (typical): $n = 1.5$
- Diamond: $n = 2.42$

The wavelength of light changes when it enters a different medium, but the frequency remains constant:

$$\lambda_n = \frac{\lambda}{n} \tag{1.6}$$

where λ is the wavelength in vacuum and λ_n is the wavelength in the medium.

1.5 Snell's Law of Refraction

When light passes from one medium to another, it bends at the interface. This phenomenon is called **refraction**.

Law 1.5.1 (Snell's Law)**.** *The relationship between the angles of incidence and refraction is:*

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{1.7}$$

where n_1 and n_2 are the indices of refraction of the two media, and θ_1 and θ_2 are the angles measured from the normal.

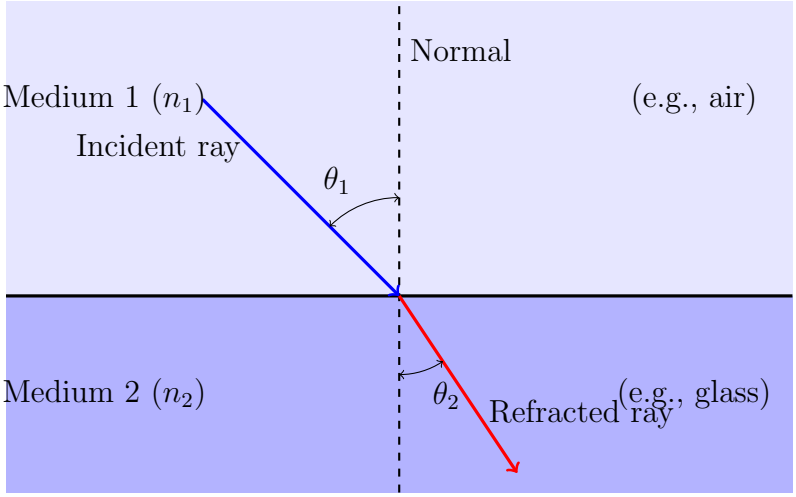


Figure 1.2: Refraction at the interface between two media

1.5.1 Derivation of Snell's Law

Snell's law can be derived using Huygens' principle or Fermat's principle of least time.

Using Fermat's Principle:

Light travels from point A in medium 1 to point B in medium 2 along the path that takes the least time.

Let the interface be at $y = 0$, point A at $(-x_1, h_1)$, and point B at $(x_2, -h_2)$. The light crosses the interface at $(x, 0)$.

Total travel time:

$$t = \frac{\sqrt{x_1^2 + h_1^2}}{v_1} + \frac{\sqrt{x_2^2 + h_2^2}}{v_2} \tag{1.8}$$

Since $v = c/n$:

$$t = \frac{n_1\sqrt{x_1^2 + h_1^2}}{c} + \frac{n_2\sqrt{x_2^2 + h_2^2}}{c} \tag{1.9}$$

For minimum time, $dt/dx = 0$. After differentiation and simplification, this yields Snell's law.

1.5.2 Refraction Cases

Case 1: Light entering a denser medium ($n_2 > n_1$)

- Light bends toward the normal
- $\theta_2 < \theta_1$
- Speed decreases, wavelength decreases

Case 2: Light entering a less dense medium ($n_2 < n_1$)

- Light bends away from the normal
- $\theta_2 > \theta_1$
- Speed increases, wavelength increases

Example

A light ray travels from air ($n = 1.00$) into water ($n = 1.33$) at an angle of incidence of 30°. Find the angle of refraction.

Solution:

Using Snell's law:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{1.10}$$

$$(1.00)\sin(30) = (1.33)\sin\theta_2 \tag{1.11}$$

$$0.500 = 1.33\sin\theta_2 \tag{1.12}$$

$$\sin\theta_2 = \frac{0.500}{1.33} = 0.376 \tag{1.13}$$

$$\theta_2 = \sin^{-1}(0.376) = 22.1 \tag{1.14}$$

The light bends toward the normal as it enters the denser medium.

Example

Light traveling in glass ($n = 1.50$) strikes the glass-air interface at 45°. Find the angle of refraction in air.
Solution:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{1.15}$$
$$(1.50)\sin(45) = (1.00)\sin\theta_2 \tag{1.16}$$
$$1.50 \times 0.707 = \sin\theta_2 \tag{1.17}$$
$$\sin\theta_2 = 1.061 \tag{1.18}$$

Wait! $\sin\theta_2 > 1$, which is impossible. This indicates **total internal reflection** occurs. We'll study this in the next section.

1.6 Total Internal Reflection

When light travels from a denser medium to a less dense medium, and the angle of incidence exceeds a certain critical angle, all the light is reflected back into the denser medium. This is called **total internal reflection**.

1.6.1 Critical Angle

The critical angle θ_c is the angle of incidence for which the angle of refraction is 90°.

At the critical angle:

$$n_1 \sin\theta_c = n_2 \sin(90) = n_2 \tag{1.19}$$

Important Equation

Critical angle formula:

$$\sin\theta_c = \frac{n_2}{n_1} \tag{1.20}$$

or

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) \tag{1.21}$$

where $n_1 > n_2$ (light traveling from denser to less dense medium).

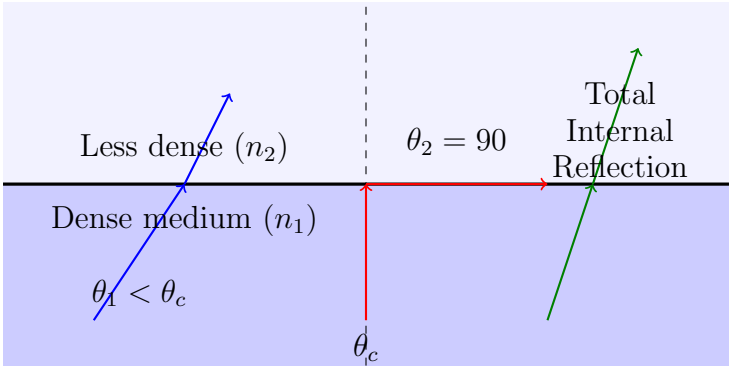


Figure 1.3: Three cases: refraction, critical angle, and total internal reflection

1.6.2 Conditions for Total Internal Reflection

Total internal reflection occurs when:

1. Light travels from a denser to a less dense medium ($n_1 > n_2$)
2. The angle of incidence exceeds the critical angle ($\theta_1 > \theta_c$)

Example

Find the critical angle for light traveling from glass ($n = 1.50$) to air ($n = 1.00$).
Solution:

$$\sin\theta_c = \frac{n_2}{n_1} = \frac{1.00}{1.50} = 0.667 \tag{1.22}$$

$$\theta_c = \sin^{-1}(0.667) = 41.8 \tag{1.23}$$

Any light ray in the glass striking the glass-air interface at an angle greater than 41.8° will be totally reflected.

Example

Calculate the critical angle for a water-air interface ($n_{\text{water}} = 1.33$).
Solution:

$$\sin\theta_c = \frac{n_{\text{air}}}{n_{\text{water}}} = \frac{1.00}{1.33} = 0.752 \tag{1.24}$$

$$\theta_c = \sin^{-1}(0.752) = 48.8 \tag{1.25}$$

This explains why, when you're underwater and look up at a steep angle, you see a mirror-like reflection of the bottom rather than the surface.

1.6.3 Applications of Total Internal Reflection

1. Optical Fibers

Light signals are transmitted through optical fibers using total internal reflection. The fiber consists of a core with high refractive index surrounded by cladding with lower refractive index. Light entering at one end undergoes multiple total internal reflections and emerges at the other end with minimal loss.

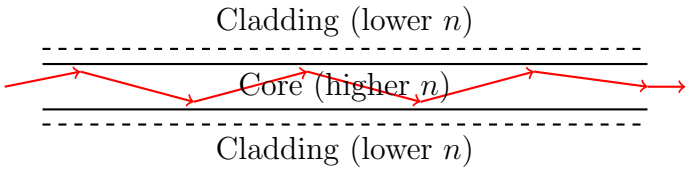


Figure 1.4: Light propagation in an optical fiber by total internal reflection

2. Prisms in Binoculars

Prisms are used to reflect light through 90° or 180° using total internal reflection, which is more efficient than mirrors.

3. Diamonds

The high refractive index of diamond ($n = 2.42$) gives a small critical angle (24.4°), causing total internal reflection of light entering the diamond, creating its characteristic sparkle.

Practice Problem

A light ray in water ($n = 1.33$) strikes the water-air boundary at 50°. Does total internal reflection occur? If not, find the angle of refraction.

Solution

First, find the critical angle:

$$\theta_c = \sin^{-1}\left(\frac{1.00}{1.33}\right) = 48.8 \tag{1.26}$$

Since $\theta_1 = 50 > \theta_c = 48.8$, **total internal reflection occurs**.
No light is refracted into the air; all light is reflected back into the water.

Chapter 2

Interference of Light Waves

2.1 Introduction to Interference

Interference is a phenomenon characteristic of all wave motion. When two or more waves overlap in space, the resultant displacement is the algebraic sum of the individual displacements. This is called the **principle of superposition**.

2.1.1 Principle of Superposition

For two waves y_1 and y_2 arriving at the same point:

$$y_{\text{total}} = y_1 + y_2 \tag{2.1}$$

For waves of the same frequency:

$$y_1 = A_1 \sin(kx - \omega t) \tag{2.2}$$
$$y_2 = A_2 \sin(kx - \omega t + \phi) \tag{2.3}$$

where ϕ is the phase difference.

2.1.2 Conditions for Interference

For stable, observable interference patterns, the sources must be:

1. **Coherent**: maintaining a constant phase relationship
2. **Monochromatic**: single wavelength (or narrow range)
3. **Same frequency**

2.2 Constructive and Destructive Interference

Important Equation

Constructive Interference occurs when waves are in phase ($\phi = 0, 2\pi, 4\pi, ...$):

$$\text{Path difference} = m\lambda, \quad m = 0, 1, 2, 3, ... \tag{2.4}$$

Amplitude: $A_{\text{max}} = A_1 + A_2$
Destructive Interference occurs when waves are out of phase ($\phi = \pi, 3\pi, 5\pi, ...$):

$$\text{Path difference} = \left(m + \frac{1}{2}\right)\lambda, \quad m = 0, 1, 2, 3, ... \tag{2.5}$$

Amplitude: $A_{\text{min}} = |A_1 - A_2|$

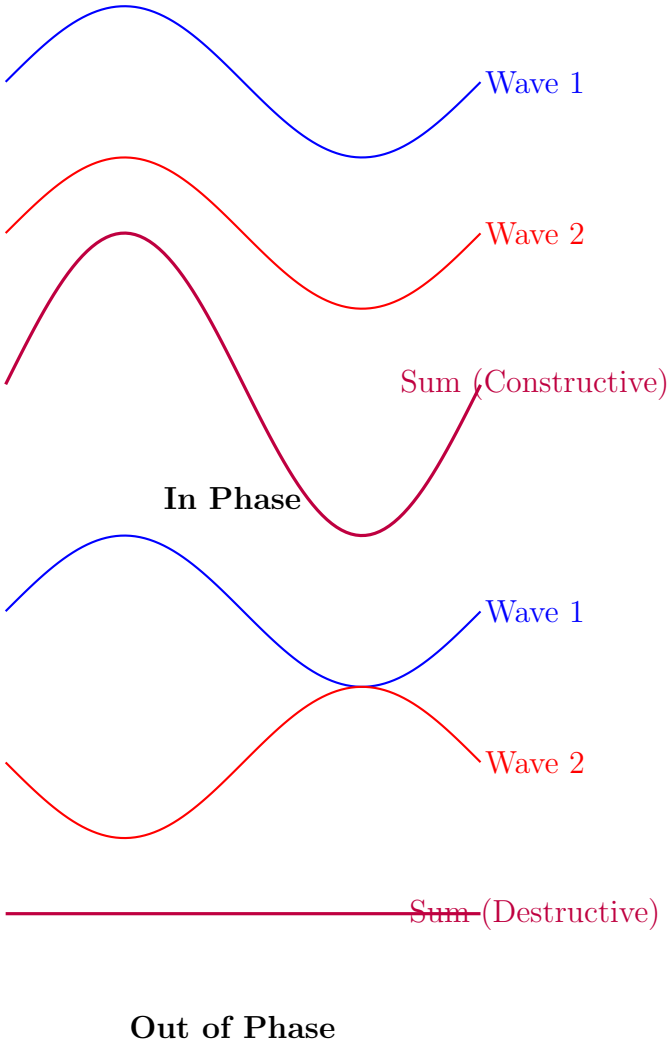


Figure 2.1: Constructive and destructive interference

2.3 Two-Source Interference

Consider two coherent point sources S_1 and S_2 separated by distance d, emitting waves of wavelength λ.

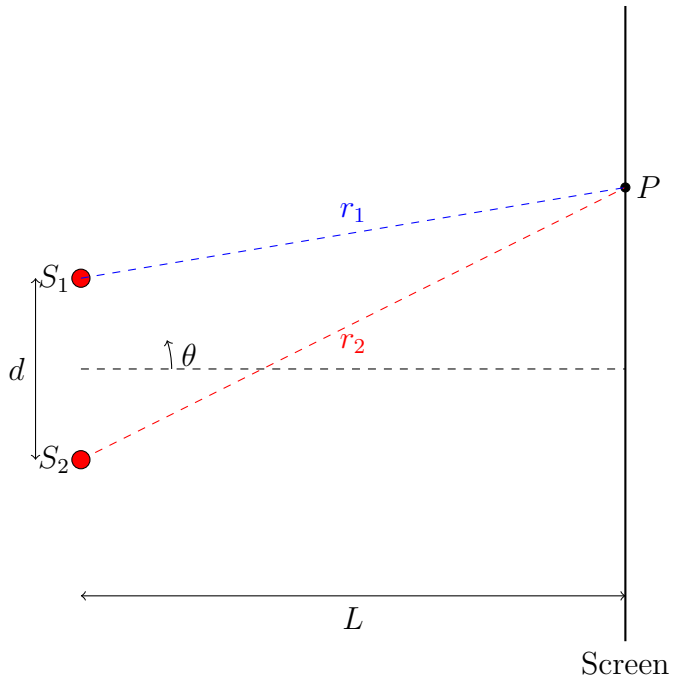


Figure 2.2: Two-source interference geometry

The path difference between the two waves reaching point P is:

$$\Delta r = r_2 - r_1 \tag{2.6}$$

For small angles (when $L \gg d$):

$$\Delta r \approx d \sin\theta \tag{2.7}$$

2.3.1 Conditions for Bright and Dark Fringes

Important Equation

Bright fringes (constructive interference):

$$d \sin\theta = m\lambda, \quad m = 0, \pm 1, \pm 2, \pm 3, \ldots \tag{2.8}$$

Dark fringes (destructive interference):

$$d \sin\theta = \left(m + \frac{1}{2}\right)\lambda, \quad m = 0, \pm 1, \pm 2, \pm 3, \ldots \tag{2.9}$$

where m is the order number of the fringe.

2.4 Young's Double-Slit Experiment

Thomas Young's double-slit experiment (1801) provided convincing evidence for the wave nature of light.

2.4.1 Experimental Setup

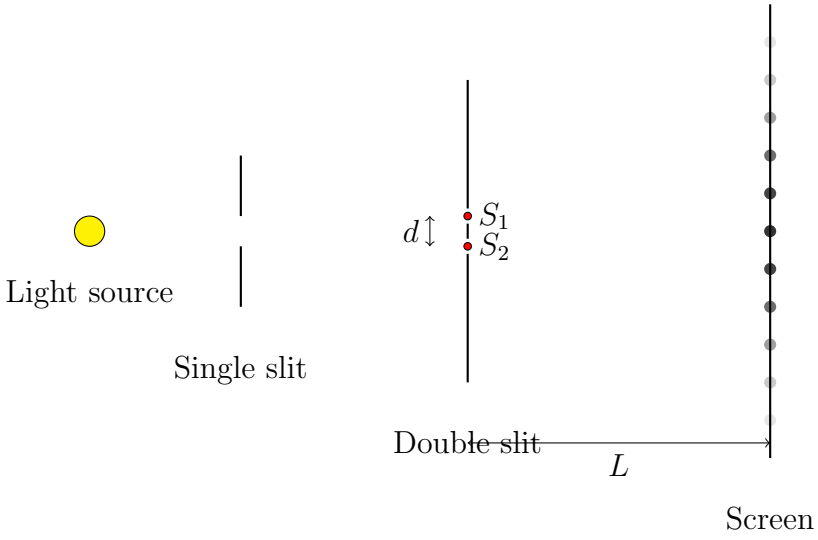


Figure 2.3: Young's double-slit experiment setup

2.4.2 Position of Fringes on Screen

For a point at distance y from the center of the screen:

$$\tan\theta \approx \sin\theta = \frac{y}{L} \tag{2.10}$$

For bright fringes:

$$d \cdot \frac{y}{L} = m\lambda \tag{2.11}$$

Important Equation

Position of bright fringes:

$$y_{\text{bright}} = \frac{m\lambda L}{d}, \quad m = 0, \pm 1, \pm 2, \ldots \tag{2.12}$$

Position of dark fringes:

$$y_{\text{dark}} = \frac{(m + \frac{1}{2})\lambda L}{d}, \quad m = 0, \pm 1, \pm 2, \ldots \tag{2.13}$$

2.4.3 Fringe Spacing

The distance between adjacent bright (or dark) fringes is:

$$\Delta y = y_{m+1} - y_m = \frac{\lambda L}{d} \tag{2.14}$$

This is constant for all fringes in the small-angle approximation.

Example

In a double-slit experiment, the slits are separated by 0.20 mm, and the screen is 1.5 m away. Light of wavelength 600 nm is used. Find:

(a) The angle to the first bright fringe

(b) The distance on the screen from the center to the third bright fringe

(c) The fringe spacing

Solution:
Given: $d = 0.20$ mm $= 2.0 \times 10^{-4}$ m, $L = 1.5$ m, $\lambda = 600$ nm $= 6.0 \times 10^{-7}$ m
(a) For first bright fringe ($m = 1$):

$$d \sin\theta = m\lambda \tag{2.15}$$

$$\sin\theta = \frac{\lambda}{d} = \frac{6.0 \times 10^{-7}}{2.0 \times 10^{-4}} = 3.0 \times 10^{-3} \tag{2.16}$$

$$\theta = \sin^{-1}(3.0 \times 10^{-3}) = 0.172 = 0.00300 \text{ rad} \tag{2.17}$$

(b) For third bright fringe ($m = 3$):

$$y_3 = \frac{m\lambda L}{d} = \frac{3 \times 6.0 \times 10^{-7} \times 1.5}{2.0 \times 10^{-4}} \tag{2.18}$$

$$= 1.35 \times 10^{-2} \text{ m} = 1.35 \text{ cm} \tag{2.19}$$

(c) Fringe spacing:

$$\Delta y = \frac{\lambda L}{d} = \frac{6.0 \times 10^{-7} \times 1.5}{2.0 \times 10^{-4}} \tag{2.20}$$

$$= 4.5 \times 10^{-3} \text{ m} = 4.5 \text{ mm} \tag{2.21}$$

Example

Two slits separated by 0.10 mm produce an interference pattern on a screen 2.0 m away. The fifth bright fringe is 6.0 cm from the center. What is the wavelength of light used?
Solution:
Given: $d = 1.0 \times 10^{-4}$ m, $L = 2.0$ m, $y_5 = 0.060$ m, $m = 5$
From $y_m = \frac{m\lambda L}{d}$:

$$\lambda = \frac{y_m d}{mL} = \frac{0.060 \times 1.0 \times 10^{-4}}{5 \times 2.0} \tag{2.22}$$

$$= 6.0 \times 10^{-7} \text{ m} = 600 \text{ nm} \tag{2.23}$$

This is orange-red light.

Practice Problem

In a double-slit experiment with slit separation 0.15 mm and screen distance 1.8 m, using light of wavelength 550 nm, calculate:

(a) The position of the second dark fringe

(b) The angular separation between the first and second bright fringes

(c) The total number of bright fringes visible if the screen extends ± 3 cm from the center

Solution

Given: $d = 1.5 \times 10^{-4}$ m, $L = 1.8$ m, $\lambda = 5.5 \times 10^{-7}$ m
(a) Second dark fringe ($m = 1$, since $m = 0$ is the first dark):

$$y_{\text{dark}} = \frac{(m + \frac{1}{2})\lambda L}{d} = \frac{(1 + 0.5) \times 5.5 \times 10^{-7} \times 1.8}{1.5 \times 10^{-4}} \tag{2.24}$$

$$= 9.9 \times 10^{-3} \text{ m} = 9.9 \text{ mm} \tag{2.25}$$

(b) For first bright: $\sin\theta_1 = \lambda/d = 3.67 \times 10^{-3}$, $\theta_1 = 0.210$
For second bright: $\sin\theta_2 = 2\lambda/d = 7.33 \times 10^{-3}$, $\theta_2 = 0.420$
Angular separation: $\Delta\theta = 0.420 - 0.210 = 0.210$
(c) Fringe spacing: $\Delta y = \lambda L/d = 6.6$ mm
Number of fringes in 6 cm range: $N = 60/6.6 \approx 9$ fringes on each side, plus center
$\rightarrow$ **19 bright fringes total**

2.5 Intensity Distribution in Double-Slit Interference

The intensity at any point on the screen depends on the phase difference between the two waves.

For two waves of equal amplitude E_0:

$$I = I_0 \cos^2\left(\frac{\phi}{2}\right) \tag{2.26}$$

where $\phi = \frac{2\pi}{\lambda}\Delta r = \frac{2\pi d \sin\theta}{\lambda}$ is the phase difference.

Important Equation

Intensity distribution:

$$I = I_{\max} \cos^2\left(\frac{\pi d \sin\theta}{\lambda}\right) \tag{2.27}$$

where $I_{\max} = 4I_0$ (for equal amplitude sources).

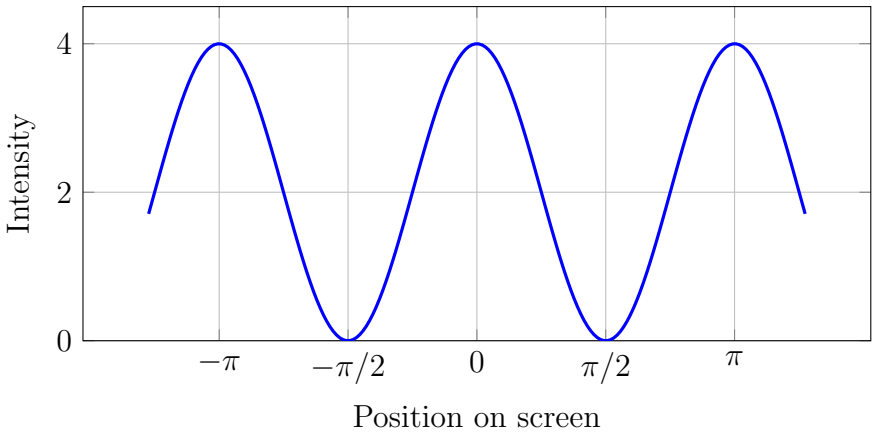


Figure 2.4: Intensity distribution in double-slit interference

Chapter 3

Thin Film Interference

3.1 Introduction to Thin Film Interference

When light reflects from the top and bottom surfaces of a thin film, the two reflected waves can interfere. This produces the colorful patterns seen in soap bubbles, oil slicks, and anti-reflection coatings.

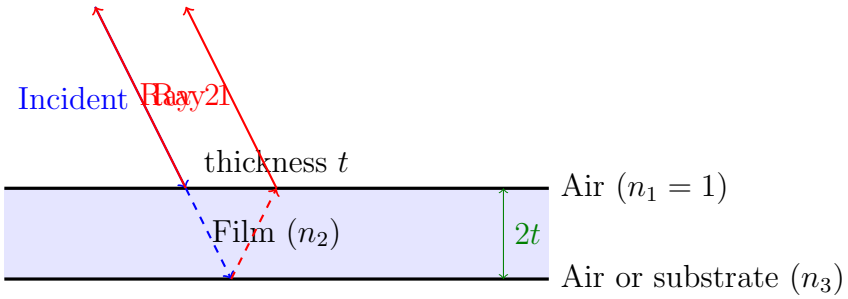


Figure 3.1: Thin film interference: two reflected rays

3.2 Phase Changes on Reflection

Key Point

When light reflects from a medium with higher refractive index than the incident medium, there is a **phase change of π radians** (equivalent to half a wavelength). When light reflects from a medium with lower refractive index, there is **no phase change**.

This is analogous to wave reflection on strings:

- Reflection from fixed end: phase change of π
- Reflection from free end: no phase change

3.3 Conditions for Constructive and Destructive Interference

Consider a thin film of thickness t and refractive index n_2, with air ($n_1 = 1$) above and below.

The optical path difference between rays 1 and 2 is:

$$\Delta = 2n_2 t \tag{3.1}$$

However, ray 1 undergoes a phase change of π (since $n_2 > n_1$), equivalent to adding $\lambda/2$ to the path difference.

Effective path difference:

$$\Delta_{\text{eff}} = 2n_2 t + \frac{\lambda}{2} \tag{3.2}$$

3.3.1 For Film with Air on Both Sides

Important Equation

Constructive interference (bright):

$$2n_2 t = \left(m + \frac{1}{2}\right)\lambda, \quad m = 0, 1, 2, 3, ... \tag{3.3}$$

Destructive interference (dark):

$$2n_2 t = m\lambda, \quad m = 0, 1, 2, 3, ... \tag{3.4}$$

Note: These conditions are **opposite** to the double-slit case because of the phase change on reflection!

3.3.2 General Case

For a film of index n_2 between media of indices n_1 and n_3:

- If $n_1 < n_2 > n_3$ or $n_1 > n_2 < n_3$: only one reflection has phase change
- If $n_1 < n_2 < n_3$ or $n_1 > n_2 > n_3$: both or neither have phase change

Count the number of phase changes and adjust accordingly.

Example

A soap bubble ($n = 1.33$) appears dark when viewed at normal incidence with light of wavelength 550 nm. What are the possible thicknesses of the film?
Solution:
Air is on both sides, so there's one phase change (at the first surface).
For destructive interference (dark):

$$2nt = m\lambda \tag{3.5}$$

$$t = \frac{m\lambda}{2n} = \frac{m \times 550}{2 \times 1.33} = 207m \text{ nm} \tag{3.6}$$

Possible thicknesses: 207 nm, 414 nm, 621 nm, ... (for $m = 1, 2, 3, ...$)
The minimum thickness is $t_{\text{min}} = 207$ nm.
Note: $m = 0$ would give $t = 0$, which is not physical.

Example

An oil film ($n = 1.45$) on water ($n = 1.33$) appears bright at 600 nm when viewed at normal incidence. Find the minimum thickness.
Solution:
Top surface: $n_{\text{air}} = 1.00 < n_{\text{oil}} = 1.45 \rightarrow$ phase change
Bottom surface: $n_{\text{oil}} = 1.45 > n_{\text{water}} = 1.33 \rightarrow$ no phase change
Only one phase change, so for constructive interference (bright):

$$2nt = \left(m + \frac{1}{2}\right)\lambda \tag{3.7}$$

$$t_{\text{min}} = \frac{\lambda}{4n} = \frac{600}{4 \times 1.45} = 103 \text{ nm} \tag{3.8}$$

(for $m = 0$)

3.4 Anti-Reflection Coatings

Camera lenses and eyeglasses are often coated with thin films to reduce reflection.

For an anti-reflection coating on glass ($n_{\text{glass}} \approx 1.5$), we use a film with $n_{\text{film}} = \sqrt{n_{\text{glass}}} \approx 1.22$ (such as magnesium fluoride, $n = 1.38$).

For destructive interference at wavelength λ:

$$t = \frac{\lambda}{4n_{\text{film}}} \tag{3.9}$$

This is the minimum thickness. Human eyes are most sensitive to $\lambda \approx 550$ nm (green-yellow), so coatings are optimized for this wavelength.

Example

Design an anti-reflection coating for glass ($n = 1.52$) using magnesium fluoride ($n = 1.38$). Find the minimum thickness for $\lambda = 550$ nm.

Solution:

For minimum reflection, we want destructive interference of reflected light.
There are phase changes at both surfaces (since $1 < 1.38 < 1.52$), so they cancel.
For destructive interference:

$$2nt = m\lambda \tag{3.10}$$

$$t_{\min} = \frac{\lambda}{2n} = \frac{550}{2 \times 1.38} = 99.6 \text{ nm} \approx 100 \text{ nm} \tag{3.11}$$

(for $m = 1$; $m = 0$ gives $t = 0$)
Actually, for best performance, we often use $t = \lambda/(4n) = 99.6$ nm if only one phase change occurs (depends on substrate).

3.5 Newton's Rings

When a plano-convex lens is placed on a flat glass plate, the air gap forms a thin film of varying thickness, creating circular interference fringes called Newton's rings.

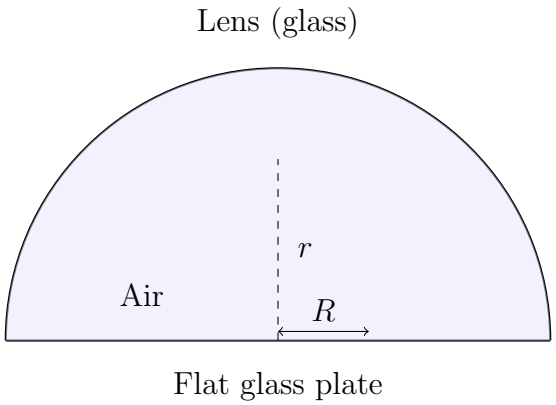


Figure 3.2: Newton's rings setup

The radius of the m-th dark ring is:

$$r_m = \sqrt{m\lambda R} \tag{3.12}$$

where R is the radius of curvature of the lens.

Practice Problem

A thin film of oil ($n = 1.50$) floats on water ($n = 1.33$). When illuminated with white light at normal incidence, the film appears green ($\lambda = 520$ nm) in reflection. What are possible thicknesses of the film?

Solution

Phase changes:

- Top (air-oil): $1.00 < 1.50 \rightarrow$ phase change
- Bottom (oil-water): $1.50 > 1.33 \rightarrow$ no phase change

One phase change total. For constructive interference (bright green):

$$2nt = \left(m + \frac{1}{2}\right)\lambda \tag{3.13}$$

$$t = \frac{(m + 0.5) \times 520}{2 \times 1.50} = 173(m + 0.5) \text{ nm} \tag{3.14}$$

For $m = 0$: $t = 86.7$ nm
For $m = 1$: $t = 260$ nm
For $m = 2$: $t = 433$ nm, etc.

Chapter 4

Diffraction

4.1 Introduction to Diffraction

Diffraction is the bending of waves around obstacles or through apertures. It is a consequence of the wave nature of light.

Key Point

Diffraction is significant when the size of the obstacle or aperture is comparable to the wavelength of the wave.

4.2 Diffraction and the Wave Theory

4.2.1 Huygens' Principle

Every point on a wavefront acts as a source of secondary spherical wavelets. The new wavefront is the envelope of these wavelets.

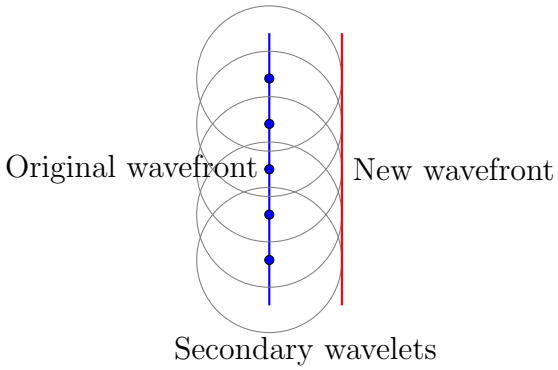


Figure 4.1: Huygens' principle: construction of wavefronts

Using Huygens' principle, we can explain:

- Reflection and refraction
- Diffraction around obstacles
- Diffraction through apertures

4.2.2 Fresnel and Fraunhofer Diffraction

Fresnel Diffraction: Source or screen (or both) at finite distance from aperture. Wavefronts are curved.

Fraunhofer Diffraction: Source and screen effectively at infinite distance. Wavefronts are plane waves. This is easier to analyze and is the case we'll focus on.

4.3 Single-Slit Diffraction

When light passes through a narrow slit of width a, it spreads out and forms a diffraction pattern on a distant screen.

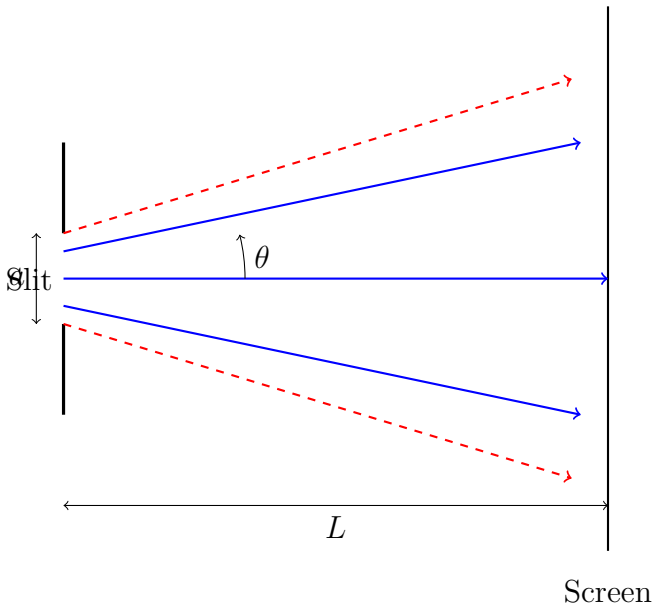


Figure 4.2: Single-slit diffraction geometry

4.3.1 Derivation of Minima Positions

Divide the slit into many point sources. Using Huygens' principle, each point emits wavelets.

Consider rays from the top and bottom of the slit at angle θ. The path difference is:

$$\Delta = a \sin \theta \tag{4.1}$$

For destructive interference (minimum), we can pair up sources from the top half with sources from the bottom half such that they are out of phase by $\lambda/2$.

This occurs when the path difference from top to bottom equals an integer multiple of wavelengths:

Important Equation

Minima in single-slit diffraction:

$$a \sin\theta = m\lambda, \quad m = \pm 1, \pm 2, \pm 3, ... \tag{4.2}$$

(Note: $m \neq 0$)

The **central maximum** is at $\theta = 0$.

4.3.2 Width of Central Maximum

The angular width from first minimum on one side to first minimum on the other side:

$$2\theta_1 = 2\sin^{-1}\left(\frac{\lambda}{a}\right) \tag{4.3}$$

For small angles:

$$\theta_1 \approx \frac{\lambda}{a} \tag{4.4}$$

The linear width on a screen at distance L:

$$w = 2L\tan\theta_1 \approx 2L\theta_1 = \frac{2L\lambda}{a} \tag{4.5}$$

Key Point

The narrower the slit, the wider the diffraction pattern.
As $a \to \lambda$, the diffraction becomes very pronounced.
As $a \gg \lambda$, the diffraction is minimal (geometric optics limit).

4.3.3 Intensity Distribution

The intensity as a function of angle is:

$$I(\theta) = I_0\left[\frac{\sin(\beta)}{\beta}\right]^2 \tag{4.6}$$

where $\beta = \frac{\pi a \sin\theta}{\lambda}$

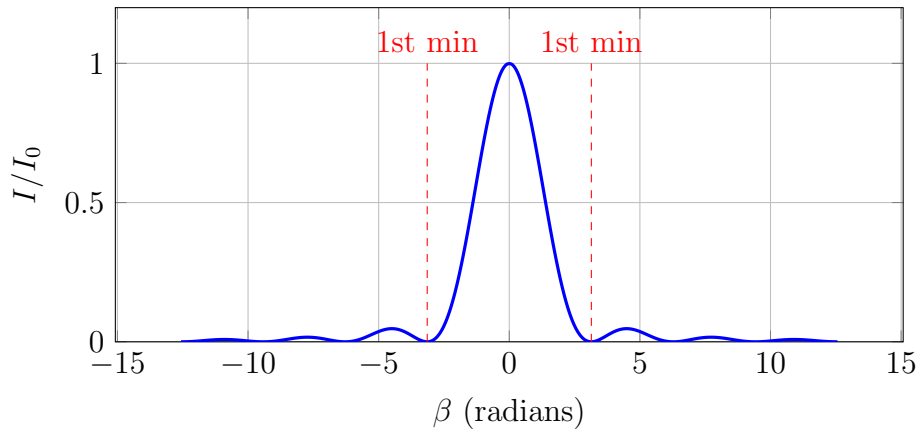


Figure 4.3: Intensity distribution for single-slit diffraction

Example

Light of wavelength 632.8 nm (He-Ne laser) passes through a slit of width 0.20 mm. A screen is placed 3.0 m away. Find:

(a) The angle to the first minimum

(b) The width of the central maximum on the screen

Solution:
Given: $\lambda = 632.8$ nm $= 6.328 \times 10^{-7}$ m, $a = 2.0 \times 10^{-4}$ m, $L = 3.0$ m
(a) First minimum ($m = 1$):

$$\sin\theta = \frac{m\lambda}{a} = \frac{6.328 \times 10^{-7}}{2.0 \times 10^{-4}} = 3.164 \times 10^{-3} \tag{4.7}$$

$$\theta = \sin^{-1}(3.164 \times 10^{-3}) = 0.181 = 3.16 \text{ mrad} \tag{4.8}$$

(b) Width of central maximum:

$$w = 2L\tan\theta \approx 2L\theta \tag{4.9}$$

$$= 2 \times 3.0 \times 3.164 \times 10^{-3} \tag{4.10}$$

$$= 0.0190 \text{ m} = 1.90 \text{ cm} \tag{4.11}$$

Example

A single slit produces a diffraction pattern on a screen 2.5 m away. The width of the central maximum is 5.0 cm. If the slit width is 0.10 mm, find the wavelength of light used.
Solution:
Given: $L = 2.5$ m, $w = 0.050$ m, $a = 1.0 \times 10^{-4}$ m
From $w = \frac{2L\lambda}{a}$:

$$\lambda = \frac{wa}{2L} = \frac{0.050 \times 1.0 \times 10^{-4}}{2 \times 2.5} \tag{4.12}$$

$$= 1.0 \times 10^{-6} \text{ m} = 1000 \text{ nm} \tag{4.13}$$

This is infrared light.

4.4 Double-Slit Diffraction

In reality, Young's double-slit experiment shows both interference and diffraction effects. Each slit produces a diffraction pattern, and the two patterns interfere.
The combined intensity is:

$$I = I_0 \cos^2\left(\frac{\pi d \sin\theta}{\lambda}\right)\left[\frac{\sin(\beta)}{\beta}\right]^2 \tag{4.14}$$

where:

- $\cos^2$ term: interference from two slits

- $[\sin(\beta)/\beta]^2$ term: diffraction from single slit
- d = slit separation
- a = slit width
- $\beta = \frac{\pi a \sin\theta}{\lambda}$

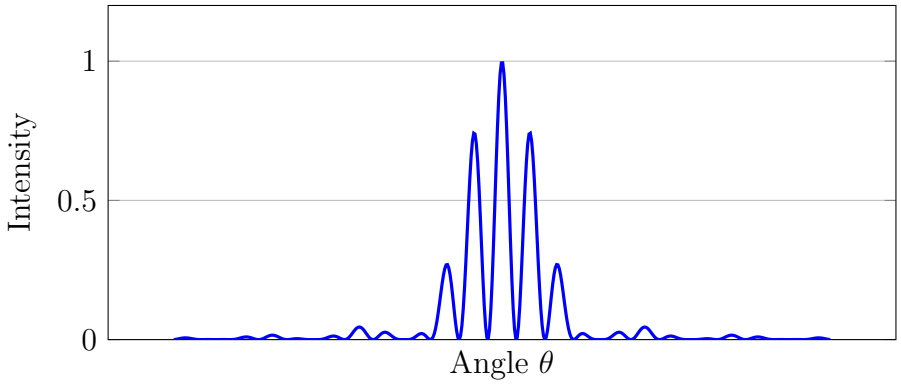


Figure 4.4: Combined interference-diffraction pattern for double slits

Key Point

The diffraction envelope modulates the interference pattern. Some interference maxima may be missing if they coincide with diffraction minima.

Practice Problem

Light of wavelength 550 nm is incident on a single slit of width 0.30 mm. Find:

(a) The angular positions of the first three minima

(b) The angular width of the central maximum

(c) If the screen is 2.0 m away, what is the linear width of the central bright fringe?

Solution

Given: $\lambda = 5.5 \times 10^{-7}$ m, $a = 3.0 \times 10^{-4}$ m, $L = 2.0$ m
(a) For minima: $a \sin\theta = m\lambda$
$m = 1$: $\sin\theta_1 = \lambda/a = 1.833 \times 10^{-3}$, $\theta_1 = 0.105$
$m = 2$: $\sin\theta_2 = 2\lambda/a = 3.667 \times 10^{-3}$, $\theta_2 = 0.210$
$m = 3$: $\sin\theta_3 = 3\lambda/a = 5.5 \times 10^{-3}$, $\theta_3 = 0.315$
(b) Angular width of central maximum: $2\theta_1 = 2 \times 0.105 = 0.210$
(c) Linear width: $w = 2L\tan\theta_1 \approx 2L\theta_1$
Converting θ_1 to radians: $\theta_1 = 1.833 \times 10^{-3}$ rad
$w = 2 \times 2.0 \times 1.833 \times 10^{-3} = 7.33 \times 10^{-3}$ m $= 7.33$ mm

4.5 Diffraction Gratings

A diffraction grating consists of a large number of equally spaced parallel slits (or reflecting grooves). It produces very sharp interference maxima.

For N slits separated by distance d:

Important Equation

Principal maxima occur at:

$$d \sin\theta = m\lambda, \quad m = 0, \pm 1, \pm 2, ... \tag{4.15}$$

This is the same condition as for two slits, but the maxima are much sharper.

4.5.1 Resolving Power

The resolving power of a grating is its ability to separate closely spaced wavelengths:

$$R = \frac{\lambda}{\Delta\lambda} = mN \tag{4.16}$$

where N is the total number of illuminated slits and m is the order.

4.5.2 Applications

- Spectroscopy: separating wavelengths in light
- Wavelength measurement
- CD/DVD reading (reflection gratings)

Chapter 5

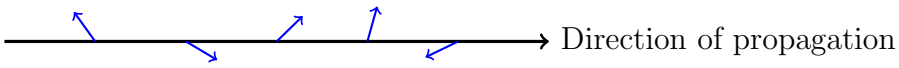
Polarization of Light

5.1 Introduction to Polarization

Polarization is a property of transverse waves. Since light is a transverse electromagnetic wave, it can be polarized.

5.1.1 Unpolarized Light

Natural light (from the sun, light bulbs) is **unpolarized**: the electric field oscillates randomly in all directions perpendicular to the direction of propagation.

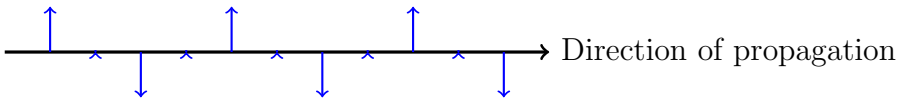


Unpolarized light: $\vec{E}$ in random directions

Figure 5.1: Unpolarized light

5.1.2 Polarized Light

Linearly polarized light: the electric field oscillates in a single plane.



Vertically polarized light

Figure 5.2: Linearly polarized light

5.2 Methods of Polarization

There are several ways to produce polarized light:

5.2.1 1. Polarization by Selective Absorption

Certain materials (like polaroid filters) absorb light with electric field in one direction and transmit light with field perpendicular to it.

5.2.2 2. Polarization by Reflection

When unpolarized light reflects off a non-metallic surface, the reflected light is partially polarized, with $\vec{E}$ perpendicular to the plane of incidence.

At a specific angle called **Brewster's angle** θ_B, the reflected light is completely polarized:

$$\tan\theta_B = \frac{n_2}{n_1} \tag{5.1}$$

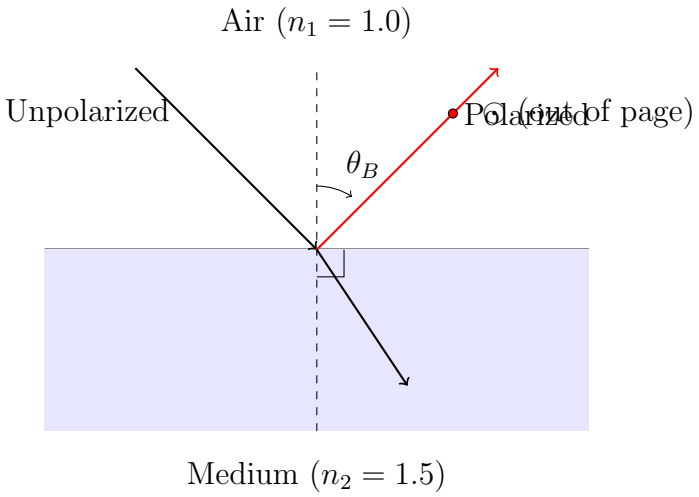


Figure 5.3: Polarization by reflection at Brewster's angle

At Brewster's angle, the reflected and refracted rays are perpendicular to each other.

Example

Find Brewster's angle for light reflecting from water ($n = 1.33$).
Solution:

$$\tan\theta_B = \frac{n_{\text{water}}}{n_{\text{air}}} = \frac{1.33}{1.00} = 1.33 \tag{5.2}$$

$$\theta_B = \tan^{-1}(1.33) = 53.1 \tag{5.3}$$

This is why polarizing sunglasses (with vertical transmission axis) reduce glare from water surfaces.

5.2.3 3. Polarization by Double Refraction

Certain crystals (like calcite) are **birefringent**: they have different refractive indices for different polarizations. An incident unpolarized ray splits into two rays:

- Ordinary ray (o-ray): follows Snell's law
- Extraordinary ray (e-ray): does not follow Snell's law

5.2.4 4. Polarization by Scattering

When light scatters off molecules in the atmosphere, the scattered light is partially polarized. This is why the sky appears polarized, especially at 90° from the sun.

5.3 Malus's Law

When polarized light of intensity I_0 passes through a polarizer with transmission axis at angle θ to the polarization direction:

Important Equation

Malus's Law:

$$I = I_0 \cos^2 \theta \tag{5.4}$$

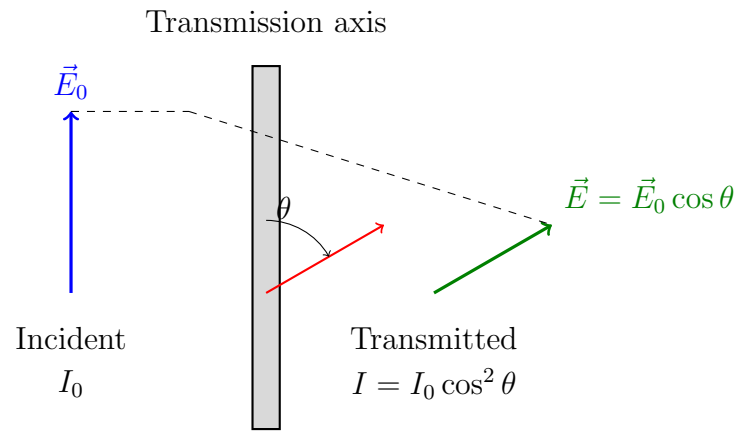


Figure 5.4: Malus's Law: intensity transmitted through polarizer

5.3.1 Derivation

The electric field component along the transmission axis is:

$$E = E_0 \cos \theta \tag{5.5}$$

Since intensity is proportional to the square of amplitude:

$$I \propto E^2 = E_0^2 \cos^2 \theta \tag{5.6}$$

Therefore:

$$I = I_0 \cos^2 \theta \tag{5.7}$$

5.3.2 Special Cases

- $\theta = 0$: $I = I_0$ (maximum transmission)
- $\theta = 90$: $I = 0$ (complete blocking)
- $\theta = 45$: $I = I_0/2$ (half intensity)

5.4 Polarizing Sheets

5.4.1 Unpolarized Light Through a Polarizer

When unpolarized light of intensity I_0 passes through a polarizer, the transmitted intensity is:

$$I = \frac{I_0}{2} \tag{5.8}$$

This is because unpolarized light can be considered as having equal components in all directions, and on average, $\langle \cos^2 \theta \rangle = 1/2$.

5.4.2 Two Polarizers (Analyzer)

When unpolarized light passes through two polarizers:

1. First polarizer: $I_1 = I_0/2$
2. Second polarizer (analyzer): $I_2 = I_1 \cos^2 \theta = \frac{I_0}{2} \cos^2 \theta$

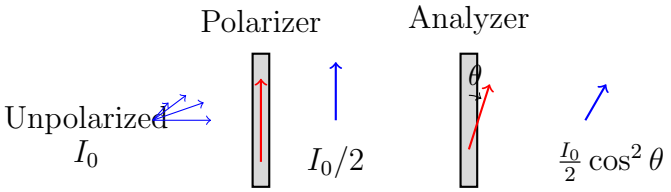


Figure 5.5: Unpolarized light through two polarizers

5.4.3 Three Polarizers

Interesting phenomenon: If you have two crossed polarizers ($\theta = 90$), no light passes through. But if you insert a third polarizer between them at $\theta = 45$, light does pass through!

$$I_3 = \frac{I_0}{2} \cos^2(45) \cos^2(45) = \frac{I_0}{2} \times \frac{1}{2} \times \frac{1}{2} = \frac{I_0}{8} \tag{5.9}$$

Example

Unpolarized light of intensity $I_0 = 100$ W/m^2 passes through two polarizers. The transmission axis of the second polarizer is at 60° to that of the first. Find:

(a) The intensity after the first polarizer

(b) The intensity after the second polarizer

Solution:
(a) After first polarizer:

$$I_1 = \frac{I_0}{2} = \frac{100}{2} = 50 \text{ W/m}^2 \tag{5.10}$$

(b) After second polarizer:

$$I_2 = I_1 \cos^2\theta = 50\cos^2(60) \tag{5.11}$$
$$= 50 \times (0.5)^2 = 50 \times 0.25 \tag{5.12}$$
$$= 12.5 \text{ W/m}^2 \tag{5.13}$$

Example

Two polarizing sheets have their transmission axes perpendicular. A third sheet is inserted between them with its axis at 45° to each. If unpolarized light of intensity I_0 is incident on the first sheet, what is the final transmitted intensity?
Solution:
After 1st polarizer: $I_1 = I_0/2$
After 2nd polarizer (at 45°): $I_2 = I_1\cos^2(45) = \frac{I_0}{2} \times \frac{1}{2} = \frac{I_0}{4}$
After 3rd polarizer (at 90° from 2nd, i.e., 45° from vertical):

$$I_3 = I_2\cos^2(45) = \frac{I_0}{4} \times \frac{1}{2} = \frac{I_0}{8} \tag{5.14}$$

Without the middle polarizer, $I = 0$. With it, $I = I_0/8$!

Practice Problem

Polarized light of intensity 200 W/m^2 is incident on a polarizing sheet with its transmission axis at 30° to the incident polarization. Find:

(a) The transmitted intensity

(b) The percentage of light transmitted

(c) At what angle would the transmitted intensity be half the incident intensity?

Solution

Given: $I_0 = 200$ W/m^2, $\theta = 30$
(a) Using Malus's law:

$$I = I_0 \cos^2\theta = 200 \times \cos^2(30) \tag{5.15}$$
$$= 200 \times (0.866)^2 = 200 \times 0.75 \tag{5.16}$$
$$= 150 \text{ W/m}^2 \tag{5.17}$$

(b) Percentage transmitted:

$$\frac{I}{I_0} \times 100\% = \frac{150}{200} \times 100\% = 75\% \tag{5.18}$$

(c) For $I = I_0/2$:

$$\frac{I_0}{2} = I_0 \cos^2\theta \tag{5.19}$$
$$\cos^2\theta = 0.5 \tag{5.20}$$
$$\cos\theta = \frac{1}{\sqrt{2}} \tag{5.21}$$
$$\theta = 45 \tag{5.22}$$

5.5 Applications of Polarization

5.5.1 1. Polarizing Sunglasses

Reduce glare from horizontal surfaces (water, roads, snow) by blocking horizontally polarized light.

5.5.2 2. LCD Displays

Liquid crystal displays use polarizers and the ability of liquid crystals to rotate the polarization of light when voltage is applied.

5.5.3 3. Stress Analysis

Transparent materials under stress become birefringent. Using crossed polarizers, stress patterns can be visualized.

5.5.4 4. 3D Movies

Modern 3D glasses use circular polarization. Left and right eye images are projected with opposite circular polarizations.

5.5.5 5. Photography

Polarizing filters reduce reflections and increase color saturation, especially in sky photography.

5.5.6 6. Optical Communications

Polarization-maintaining fibers are used in telecommunications and sensing applications.

Summary and Key Equations

Reflection and Refraction

- Law of reflection: $\theta_i = \theta_r$
- Snell's law: $n_1 \sin\theta_1 = n_2 \sin\theta_2$
- Index of refraction: $n = c/v$
- Critical angle: $\sin\theta_c = n_2/n_1$ (for $n_1 > n_2$)

Interference

- Constructive: path difference $= m\lambda$
- Destructive: path difference $= (m + 1/2)\lambda$
- Double slit bright fringes: $d \sin\theta = m\lambda$
- Fringe spacing: $\Delta y = \lambda L/d$
- Thin film (one phase change): bright when $2nt = (m + 1/2)\lambda$

Diffraction

- Single-slit minima: $a \sin\theta = m\lambda$, $m = \pm 1, \pm 2, ...$
- Central maximum width: $w = 2\lambda L/a$
- Grating maxima: $d \sin\theta = m\lambda$

Polarization

- Malus's law: $I = I_0 \cos^2\theta$
- Unpolarized through polarizer: $I = I_0/2$
- Brewster's angle: $\tan\theta_B = n_2/n_1$

Practice Problems

Mixed Problems Set

Practice Problem

Light travels from air into a glass block at 30°. The refracted angle is 19.5°. Find the refractive index of glass and the critical angle for glass-air interface.

Practice Problem

In a double-slit experiment, the 5th bright fringe is at the same position as where the 6th dark fringe of another wavelength would be. If the first wavelength is 600 nm, find the second wavelength.

Practice Problem

A soap film ($n = 1.33$) of thickness 300 nm is illuminated by white light at normal incidence. What wavelengths in the visible range (400-700 nm) will be strongly reflected?

Practice Problem

A single slit of width 0.12 mm produces a diffraction pattern. The second minimum is at 1.5 cm from the central maximum on a screen 2.0 m away. Find the wavelength.

Practice Problem

Three polarizers are arranged with their axes at 0°, 45°, and 90° respectively. Unpolarized light of intensity 80 W/m^2 is incident on the first. Find the intensity emerging from the third polarizer.

End of Textbook